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Interpretations for Observations of Astronomical Masers

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ABSTRACT

Studies of astronomical masers have progressed in parallel with research on complex molecules, beginning with the original detections of both which occurred some twenty-five or so years ago. Basic aspects of the interpretation of the observational data are discussed with particular application to the 22 GHz water masers in regions of star formation. Specific issues include the nature of the gas dynamical environment based on pumping and other considerations, the structure and energetics from information in the spectral line profiles, and inferences about the strengths of magnetic fields at the highest gas densities from the polarization of maser radiation.

1. INTRODUCTION

The study of astronomical masers has developed in parallel with that of complex molecules during the past 25 or so years. The original detections of the strong masers have occurred—OH at 18 cm, H_2O at 1.3 cm and SiO at 3.5 mm. Numerous other strong masing transitions of these and other (especially CH_3OH) species have subsequently been detected and studied at wavelengths into the submillimeter regime. Because of their small sizes and high surface brightnesses, masers are ideal probes for astronomical phenomena at the highest spatial resolution using the techniques of long baseline, radio interferometry. Astronomical masers are associated with active regions of the molecular gas, mainly related to star formation and to the return of matter to the gas from stars. They also occur near the centers of activity in the nuclei of other galaxies. Some of the earliest indications of the bipolar flows of gas in regions of star formation came from the observation of the high velocity masers. The structure of circumstellar matter near late-type giants has been delineated and the sizes of the circumstellar shells have been determined from the time delays in the response of the maser emission to the time variations in the infrared emission of the central star.

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I will focus upon issues centered around the interpretation of observations of a particluar type of astronomical maser—the interstellar (and now extragalactic) 22 GHz water masers. The relatively recent detection of a number of other masing transitions of the water molecule confirms that water masers are a basic component of the astronomical environment. The underlying issues for the 22 GHz masers are generally, and in some cases quite specifically, relevant to the interpretation of other types of astronomical masers, as well. Of the types of masers, the 22 GHz water masers seem to provide the greatest challenge to the interpretations. Their study does, however, offer the opportunity for significant rewards in astronomical information. The 22 GHz masers tend to be nearest to the centers of star formation and are also located near the nuclei of other galaxies. They possess the highest surface brightness, greatest luminosities and smallest angular sizes—qualities which make them especially valuable probes of astronomical phenomena at the highest spatial resolution. Information is obtained on high velocity outflows and, possibly, on disks associated with protostellar environments and with the nuclei of other galaxies. Astronomical distances on the galactic (and potentially extragalactic) scale are obtained from a statistical analysis of the motions of individual masing spots. Strengths for the magnetic fields at the highest densities in the star forming gas have been inferred from observations of the circular polarization of the radiation. Understanding the very high brightness temperatures and the tight beaming of the maser radiation places the most severe restrictions upon the theory for the pumping and the radiative transfer, as well as upon the nature of the astronomical environments. If limitations due to time, space or the author's ability to provide a coherent presentation require that the focus be limited to only one type of maser, the 22 GHz water masers are a reasonable choice.

The presentation here is organized into three parts which are centered around the gas dynamical nature and the pumping of the water masers (Section 2), the structure and energetics based on information in spectral features (Section 3) and the inferences about the strengths of magnetic fields in the star forming gas from the polarization characteristics of the radiation (Section 4).

2. THE NATURE AND ENVIRONMENT OF THE ASTRONOMICAL WATER MASERS

The 22 GHz masing transition of water occurs between the 6_{16} and 5_{23} rotational energy levels which lie at an energy of about $E/k \simeq 600$ K above the ground state. Each rotational level consists of three hyperfine states. There are then six radiative transitions. Calculations indicate that the "22 GHz maser line" probably is a merged profile due to the strongest three of these hyperfine transitions (Nedoluha and Watson 1991). Other, newly detected masing transitions (e.g., Cernicharo et al. 1990; Menten et al. 1990) occur between energy levels that are even higher as well as lower in energy. Infrared transitions also connect these masing states to other rotational (and vibrational) states and tend to have wavelengths of about 100 microns or shorter. Gas temperatures greater than 300 - 400 K, which are warmer than the 50 K or so that are typical of molecular clouds, are immediately suggested in order to elevate the water molecules into these high lying states.

To maintain an inverted population for masing, it is necessary that the populations of the masing molecules be kept away from thermodynamic equilibrium. This might be done by a difference between the kinetic temperature of the gas and the effective temperature of the infrared radiation which is emitted and absorbed by dust grains (hence, the "hot grains/cold gas" and "hot gas/cold grains" scenarios). It might also be achieved by a temperature difference between the particles that collisionally excite the water molecules—hydrogen molecules and the electrons, or the positive ions. At this time, none of the specific scenarios that utilize these somewhat subtle causes for the pumping of the 22 GHz masers seem to be adequate (e.g., Anderson and Watson 1990). As a result, attention has returned to the old idea that non-equilibrium populations are maintained by the escape of infrared, spectral line radiation associated with transitions between the masing states and other states of the water molecule. Collisions with hydrogen elevate the water molecules into excited states from which infrared, radiative cascades occur. The molecular physics of the cascade, in which the optical depths of the infrared transitions typically are large, determines the inversion of the radio frequency masing transitions. This, too, can be viewed as a "two-temperature" scenario. The effective temperature of the radiation is lowered from the kinetic temperature by the escape of radiation, and can vary from one infrared transition to another as a result of differences in their optical depths. This "line leaking", or IR escape scenario for the pumping of masers was recognized long ago (Jefferies 1971) and calculations were performed at that time which provide the essential results for the predicted pumping for H_2O masers (deJong 1973; Strelnitskij 1973). Subsequent calculations of this type in recent years differ by utilizing new collision cross sections that have been provided by chemical physicists, by utilizing escape probabilities for the infrared radiation based upon the large-velocity-gradient approximation instead of those for a static gas, and by including more molecular states to provide predictions about the new masing transitions of water that have been discovered in recent years. The accuracy in the application of the "new" collision cross sections also is unclear since they are actually calculated for "helium-like" molecular hydrogen (i.e., the internal rotational and vibrational structure of the H_2 is ignored). Differences between the type of escape probability treatment that is employed for the infrared radiation are almost certainly less important (they both tend to be proportional to [optical depth]$^{-1}$ at high optical depths which are relevant here) than the uncertainty in applying a simple escape probability treatment at all. In any case, all of the calculations of this IR escape scenario yield results that are not meaningfully different with regard to the main issue—the high apparent luminosities and extreme brightness temperatures of the 22 GHz water masers. This is not at all surprising since this type of maser scenario is constrained by the "thermodynamic limit" that was recognized in early investigations (Goldreich and Kwan 1974b; Rank, Townes and Welch 1971).

The idea of the "thermodynamic limit" is that, for every maser photon that is produced, at least one (approximately) infrared photon must escape from the masing region to produce the inversion . The relevant infrared photons would be expected to arise from one or a few transitions involving the masing states or nearby states. Since the infrared transitions are not masing, the maximum number of infrared photons that can be emitted from the surface of the masing gas is that due to optically thick transitions in thermodynamic equilibrium—the number given by the intensity of the Planck distribution (at the temperature of the gas) for frequencies within the breadth of a spectral line. To see what this means quantitatively, consider a masing cylinder of gas. The "cylinder" is not necessarily a cylindrically shaped gas cloud but is more likely to be a cylindrical region in the distribution of excitation or in which the velocity differences are small enough to create "coherent" paths for the maser radiation. Recognizing that the maser radiation must be significantly beamed, we choose the length ℓ for the cylinder to be much greater than its diameter d. Because of the exponential amplification for maser radiation, most of the maser radiation emerges from the ends of the cylinder whereas most of the infrared radiation escapes through the sidewalls. The number of maser photons that escape per unit time is then approximately

$$\frac{2\nu_m^2}{c^2} \times \frac{kT_m}{h\nu_m}\Delta\nu_m \times \Delta\Omega_m \times 2\pi d^2 \tag{1}$$

where T_m, ν_m, and $\Delta\nu_m$ are the brightness temperature, frequency and spectral line breadth of the maser radiation. It is beamed into a solid angle $\Delta\Omega_m$ as it emerges through the caps (with area πd^2) of the cylinder. The Rayleigh-Jeans approximation is utilized here as well as in equation (2) for the infrared radiation. The analogous expression for the rate of escape of infrared photons in a spectral line is approximately

$$\frac{2\nu_{ir}^2}{c^2} \times \frac{kT_{ir}}{h\nu_{ir}} \times \Delta\nu_{ir} \times \Delta\Omega_{ir} \times \pi\ell d \tag{2}$$

For beaming of maser radiation by a long cylinder $\Delta\Omega_m \simeq d^2/\ell^2$, whereas for escape of infrared from the sidewalls $\Delta\Omega_{ir} \simeq 2\pi$. The spectral linebreadths $\Delta\nu_m$ and $\Delta\nu_{ir}$ should be comparable when expressed in terms of Doppler velocities. The requirement that the expression of equation (2) be greater than that of equation (1) is then

$$T_m < 2\pi\left(\frac{\nu_{ir}}{\nu_m}\right)^2\left(\frac{\ell}{d}\right)^3 T_{ir} \tag{3}$$

The infrared transitions between the masing and the nearby states have wavelengths of about 100μ and the gas kinetic temperature is less than about 10^3K so that $T_m \lesssim 10^8(\ell/d)^3$ for the 22 GHz masers. Thus, aspect ratios $(\ell/d) \gtrsim 100$ are required to understand the observed brightness temperatures $T_m \gtrsim 10^{14}$K. Detailed calculations yield similar results.

It has thus been recognized for some twenty years that the pumping required to produce the high brightness temperatures of the 22 GHz water could be "understood" if one were willing to make the extreme assumption that $(\ell/d) \gtrsim 100$ *for masing cylinders (e.g.,* *Goldreich and Kwan 1974b; Strelnitskij 1973, 1984)!* In the absence of significant independent evidence, the assumption that $(\ell/d) \gtrsim 100$ has seemed to be an implausibly favorable assumption. Until recent years, the effort has thus been directed toward identifying pumping mechanisms that are inherently more powerful than this "infrared escape" scenario. Lack of success has apparently motivated recent investigators to return to the earlier scenario and to advocate $(\ell/d) \gtrsim 100$. Until very recently (see Section 3), there have only been qualitative arguments for such aspect ratios that are not significantly more advanced or compelling than have been available for the past twenty years. The large number of additional masing transitions of H_2O that have been detected in recent years does, however, require a quite general and robust cause for the inversion. This also seems to favor an "infrared escape" scenario.

The cause for the elevated kinetic temperatures of the masing gas above the 50 K or so that is typical of molecular clouds is another key issue in understanding the water masers. Because the 6_{16} and 5_{23} levels lie some 600 K above the ground state, the populations of these states are quite sensitive to the kinetic temperature. Calculations indicate that minimum temperatures of 300-400 K are necessary for the 22 GHz masers (e.g., Kylafis and Norman 1991). Somewhat higher temperatures seem to be required for certain of the newly detected masing transitions of water (Neufeld and Melnick 1991; Melnick et al. 1993). Shock waves are commonly associated with elevated kinetic temperatures in the interstellar gas. Water masers typically exhibit velocities up to 10-20 km s^{-1}, and sometimes 100-200 km s^{-1}, relative to the velocity of the molecular cloud in which they are located. They are frequently known to be in the neighborhood of HII regions which can provide the pressure to drive shock waves into the surrounding neutral gas. It was thus immediately recognized in the 1970's that the warm gas behind a shock is a natural way in which to understand the cause for the elevated gas temperatures. Calculations were performed at that time in which it was concluded that the collisional/infrared escape scenario for excitation in a shock wave would produce brightness temperatures as high as 10^{15} K in a gas with a density of about 10^9 K at about 500 K if the maser radiation is beamed into a small solid angle of $10^{-4} - 10^{-5}$sr (Strelnitskij 1973; Schmeld, Strelnitskij and Muzylev 1976). Current calculations give almost identical results for 22 GHz masers in shocks.

Where current calculations for shock excitation do offer the potential for some significant advances over the earlier work is in relation to the size of the masing region and in delineating more precisely the type of shock. To obtain paths of sufficient optical depth in the warm gas for the required maser amplification, the maser radiation is imagined to propagate parallel to the shock front. The length of the region behind the shock front (i.e., measured parallel to the shock velocity) in which there is strong inversion is then the approximate diameter of the masing spot that is observed. A problem arises for "ordinary" shocks. At the relevant gas densities in the 22 GHz masers ($\simeq 10^9$ cm^{-3}), the gas cools rapidly through the temperature regime $(300 - 1000$ K) that seems to be appropriate for the masing. The length of this regime is clearly less than the diameters of $10^{13} - 10^{14}$ cm that are observed. This has led to the proposal that dissociating J-shocks provide the necessary environment for the water masers (McKee and Hollenbach 1980). In these shocks, the hydrogen molecules that have been dissociated at the shock front are found to recombine when the gas has cooled to about 400 K—an ideal temperature for water masers. If the recombination energy goes into heating the gas, the gas will remain near 400 K for a longer time and hence a longer distance behind the shock front, leading to a larger diameter for the masing region. There is then a "shoulder" in the graph of temperature versus distance behind the shock front. This region may be as long as the 10^{13} cm which is needed for most masers. To obtain a lengthier masing gas behind the shock front that is required for larger masers, it seems to be necessary to invoke magnetic fields in addition to the recombination energy. Pressure due to magnetic fields of an appropriately chosen strength can, in principle, aid in extending the region of the warm gas by halting the increase in gas density in the post-shock region when the optimal physical conditions have been achieved. Dissociating shocks certainly are likely and sometimes may well impinge upon pre-shock gas with a density of about 10^7 cm^{-3} as is necessary to yield the conditions for the 22 GHz masers in the postshock region. On the other hand, for a number of reasons it is unlikely that dissociating J-shocks are the cause for the bulk of the radiation of interstellar and extragalactic water masers as has recently been advocated (Elitzur, Hollenbach and McKee 1989), especially at 22 GHz. i) Shocks are introduced into the interpretation of water masers mainly to provide a cause for the enhancement in the kinetic temperature. This increase is only about 0.03 eV per molecule to reach 400 K whereas dissociation requires an energy input that is at least equal to the binding energy of H_2 (4.5 eV per molecule). Less than one percent of the energy that is injected is actually required for achieving the temperatures for masers. That is, to heat the gas by only a few hundred Kelvins, the gas is first raised to some 10^5 K in this scenario. It seems likely that nature finds a more "energetically efficient" means than dissociating shocks for creating these masing environments which occur commonly. ii) Shock velocities greater than 30 km s^{-1} are required for dissociating J-shocks to produce the masing environment. According to the review of Genzel (1986), most of the 22 GHz maser radiation arises from gas with velocities near the rest velocity of the associated, quiescent molecular cloud (that is, less than 20 km s^{-1}; see also, Gwinn, Moran and Reid 1993). In a straightforward scenario, the shock would be caused by an enhancement in the pressure due to a stellar outflow (e.g., a wind or jet) or an HII region, most likely associated with a proto- or newly formed star with the velocity of the molecular cloud. The masers would then ordinarily be imagined as in the gas that is swept up by a uniformly expanding shock. In this picture, the observed velocities of the masers relative to the molecular cloud (the expansion velocity) must be essentially the same as the shock velocity. Dissociative shocks would be then excluded as the cause for the bulk of the 22 GHz maser emission. More complicated scenarios can, no doubt, be imagined in which the observed expansion velocity of the masers is not equal to the shock velocity. The necessity for additional complicating assumptions does, however, reduce the likelihood for such as the general interpretation for a widely occurring phenomenon. iii) The key aspect of dissociating shocks—the release of energy to heat the gas from the recombination of

H_2—is open to doubt. It requires that a large fraction of the energy that is released when an H_2 molecule forms on the surface of a dust grain (at grain temperatures of about 50 K) remain with the newly formed molecule as translational and vibrational energy. It might instead be absorbed by the dust grain. There seems to be no clear evidence in favor of either possibility. iv) Magnetic pressure is involved to understand the sizes of the larger 22 GHz water masers. The required strengths of these magnetic fields (Elitzur, Hollenbach and McKee 1989, equation 4.6) are larger by about a factor of ten than the fields that have actually been detected in 22 GHz water masers by Fiebig and Güsten (1989) [see also Section 4]. v) A detailed comparison of the observed intensities of several masing transitions of water indicates that the gas temperature in the masing region is significantly higher than the 400 K of the post-shock, recombination region of dissociating shocks in which the water masers are proposed to occur (Melnick et al. 1993). Apparently, this temperature is tightly constrained in dissociating J-shocks and cannot be raised to the necessary temperatures simply by adjusting parameters.

In summary, the outstanding issue for interpreting the 22 GHz water masers has historically been understanding the brightness temperatures that range up to and perhaps somewhat beyond 10^{15} K. On this issue, the recent calculations for the maser emission associated with shocks yield results that are little different from the early work of Strelnitskij and collaborators. All are based upon the infrared escape scenario and are thus constrained by the "thermodynamic limit" (equation 3). Apparent differences arise mostly from the beaming angle (or "aspect ratio") that is employed—a quantity that is obtained simply by assumption and does not follow from such calculations. To obtain the beaming, the masing region ordinarily is considered to be a cylinder—formed either from (i) actual variations in the density and excitation, or (ii) from gradients in the velocity. For the same numerical value of the "aspect ratio" for the cylinder in the two cases, the beaming angle at high brightness temperatures is smaller in case (i) by a factor of about 30 than is the beaming angle obtained when the aspect ratio is expressed as the ratio of the velocity gradients that delineate the cylinder (based on the commonly utilized LVG approximation). Calculations in which the aspect ratio refers to cylinders of case (i) will thus appear to achieve higher brightness temperatures than calculations for the same aspect ratio in case (ii), but this is an artifact due to the difference in the beaming angles that is thus being assumed (see Kylafis and Norman 1991).

3. LUMINOSITY, GEOMETRY AND THE DEGREE OF SATURATION FROM THE INTERPRETATION OF SPECTRAL LINE PROFILES

The spontaneous or incident continuum "seed" radiation, that is amplified to become the maser radiation, has a relatively broad range of frequencies. In the initial, unsaturated regime of the amplification, the optical depth is greatest for frequencies that correspond to molecular velocities near the center of the Maxwellian distribution. Since the amplification varies exponentially with the optical depth, intensities near the center grow more rapidly than those in the wings with the result that the spectral line narrows to a breadth given approximately by $\Delta v \simeq v_{th}\tau_o^{-\frac{1}{2}}$ (FWHM expressed as a velocity) where v_{th} is the thermal breadth (FWHM) of the Maxwellian distribution and τ_o is the optical depth at line center ($\simeq$ 25 for intense 22 GHz water masers). When the maser becomes saturated at line center, the difference between the populations of the upper and lower molecular states is reduced near the center of the velocity distribution below its value for a Maxwellian distribution. The amplification in the wings is then increased relative to that at line center and the spectral profile of the maser radiation rebroadens as indicated in Figure 1 to the thermal breadth of the gas. If the rate for the relaxation of molecular velocities Γ_v is faster than the decay rate Γ for the excitation, the rebroadening is postponed until the rate R for stimulated emission exceeds Γ_v. For the 22 GHz water masers, Γ_v does exceed Γ by a factor of ten or more. Velocity relaxation is mostly due to trapped infrared radiation (Goldreich and Kwan 1974a), though elastic collisions (Nedoluha and Watson 1988) make a minor contribution. The magnitude for Γ_v can be determined reliably and is about $2s^{-1}$ (Anderson and Watson 1993). Spectral line profiles for even the brightest 22 GHz water masers are clearly less than the 1 km s^{-1} (FWHM) breadth of a Maxwellian at 400 K—the approximate minimum temperature required for the excitation (because of the blending of the hyperfine components, Δv for the fully rebroadened spectral line should actually be about 1.7 km s^{-1} as shown in Figure 1 when the gas temperature is 400 K). This immediately means that $R < \Gamma_v(\simeq 2\ s^{-1})$. The rate R for stimulated emission is given by

$$R \simeq AkT_b\Delta\Omega/4\pi h\nu \tag{4}$$

where A is the Einstein coefficient for the masing transition, T_b is the observed brightness temperature and $\Delta\Omega$ is the solid angle into which the maser radiation is beamed. From the upper limit to R based on the observed linebreadth, together with the observed value for T_b, an upper limit for $\Delta\Omega$ follows immediately from equation (4) as does the luminosity L ($L \simeq \pi d^2 2\nu^2 kT_b\Delta\Omega\Delta\nu/c^2$ for a maser with an observed diameter d and a linebreadth $\Delta\nu$). Although the observed spectral line profiles might be "contaminated" by various additional effects, all such effects that have been imagined tend to increase the linebreadth (see below). The upper limits obtained by the foregoing reasoning are thus unaffected by such uncertainties. I emphasize that there is minimal uncertainty in the value of R at which rebroadening occurs. Regardless of the importance of velocity relaxation, the spectral line rebroadens when R is approximately equal to the Einstein A coefficients for the infrared transitions that involve the masing state ($\simeq 1s^{-1}$) (Nedoluha and Watson 1991).

Application of the foregoing reasoning to some of the most intense 22 GHz masers (the outbursts in Orion and W49) for which $\Delta v \simeq$ 0.6 km/s and $T_b \gtrsim 10^{15}K$ yields $R \lesssim 1s^{-1}$ and $\Delta\Omega \lesssim 10^{-5}$ sr. If the masers are cylinders of length ℓ, $\Delta\Omega \simeq (d/\ell)^2$ so that $\ell \gtrsim 3 \times 10^{15}$ cm when $d \simeq 10^{13}$ cm as is typical. Such long, narrow tubes are difficult to imagine. It is, perhaps, easier to imagine the small beaming angle as due to the interaction of distinct, well separated masing components—a scenario that we have shown to be plausible (Deguchi and Watson 1989). The longstanding puzzle of the high brightness temperatures of the 22 GHz masers is thus largely resolved. It is not due to some highly efficient, unrecognized pumping mechanism. It is probably a result of the simplest possibility—the infrared escape from a warm gas that is most likely heated by a shock, essentially as calculated by Strelnitskij and collaborators in the 1970's (also de Jong 1973). With independent evidence based on the spectral linebreadths, the extremely small beaming angles $\Delta\Omega$ (e.g., equation 4) that are required—which previously seemed implausible—now seem plausible. As noted in Section 2, problems do arise in attempting to construct a specific type of shock scenario that can produce masers with the observed sizes and other properties. It is, as yet, an unresolved issue.

As observers, we are presumably not located in an especially favorable direction in relation to the molecular clouds that contain the masing spots. There must then be about as many masing spots beamed into any other direction. The total number in all directions is thus approximately the number that we see multiplied by $(4\pi/\Delta\Omega)$ for those with a particular value of $\Delta\Omega$. The total number can be quite large since $\Delta\Omega$ is small—evidence in favor of the idea of separated, interacting components as opposed to long, continuous tubes. For the entire statistical collection of masing spots within a molecular cloud, the total luminosity is independent of $\Delta\Omega$. Although the total number of masing spots must increase as $(4\pi/\Delta\Omega)$, the luminosity of each spot is proportional to $T_b\Delta\Omega$ and T_b is already specified by the observations.

The above description of how the spectral line profile first narrows and then rebroadens with increasing saturation is, implicitly, based on the idealization that the rays of maser radiation are parallel (the "linear maser approximation"). It is expected to be a useful guide because the radiation tends to be tightly beamed within a maser. Detailed calculations were presented some time ago (Bettwieser 1976) which seemed to indicate otherwise—in particular, that rebroadening would be suppressed for a spherical maser. To assess this possiblity, we have recently performed computations for the spectral line profile of the radiation that would be observed from a spherical masing region (Emmering and Watson 1993) which are more accurate than those of previous investigations. Based on our calculation, the spectral line profile for a spherical maser does rebroaden in essentially the same manner as that for a linear maser. Its behavior is indicated by the asterisks in Figure 1. Other issues were also clarified in our study of the frequency dependent, radiative transfer in a spherical maser. In contrast to the results from certain recent investigations in the literature, we find i) that the increase in apparent size when measured at frequencies away from line center is small and probably not significant at intensities that are appreciable, and ii) that the "standard approximation" for most of the frequency dependent radiative transfer is adequate for the basic features of spherical masers that have been investigated.

4. MAGNETIC FIELDS IN REGIONS OF STAR FORMATION

Considerable progress has been made in recent years in delineating the strength of the magnetic field in the relatively diffuse interstellar gas (densities less than about 10^3 cm^{-3}) utilizing the "thermal" emission of H at 21 cm and OH at 18 cm (e.g., Heiles et al. 1993). Masers seem to provide the best opportunity for extending our knowledge of magnetic fields to the high gas densities that are most directly associated with centers of activity related to star formation and other phenomena. Identification of Zeeman pairs of lines in the spectra of 18 cm OH masers in these regions indicates the presence of magnetic fields that typically are a few milligauss. These fields are relevant for gas densities no greater than about 10^7 cm^{-3} because the inversion for the 18 cm masing transitions of OH is quenched at approximately this density. For data at still higher densities and closer to the centers of the active phenomena, the 22 GHz water and the SiO masers which seem to occur at about $10^9 - 10^{10}$ cm^{-3}, must be utilized. Evidence that the information about magnetic fields obtained from masers is generally relevant (and not indicative only of peculiar conditions in masing environments) includes the observations which indicate that the directions of these fields tend to be similar to the directions of the galactic magnetic field (Reid and Silverstein 1990). If masers are in a post-shock gas, the strengths of the fields that are inferred can potentially be related to the structure of the shock, to the gas dynamics in the region, and to the strength of the magnetic field in the ambient, pre-shock gas. The strengths of the magnetic fields at the highest gas densities bear upon the role of magnetic fields in the formation of stars.

Unlike the 18 cm OH masers for which magnetic fields of a few milligauss cause the transition to split into distinct Zeeman components, the Zeeman components of H_2O and SiO masers are separated by much less than a spectral linebreadth. The magnetic moment of OH is larger by a factor of about 1000 due to its unpaired electron. What is then sought in the spectra of the H_2O and SiO masers is net circular polarization within the single spectral feature—an antisymmetric profile for the Stokes V polarization parameter in the ideal case with no velocity gradients or hyperfine structure. The expected fractional circular polarization is small and difficult to measure. It has, however, been detected in recent years at a level of about 10^{-3} (fractionally) in the spectra of the 22 GHz masers in regions of star formation (Fiebig and Güsten 1989; Zhao, Goss and Diamond 1993) and up to nearly 0.1 fractionally in the 43 GHz, circumstellar SiO masers (Barvainis, McIntosh and Predmore 1987).

A straightforward Zeeman interpretation for these data yields magnetic fields up to about 0.1 G and 100 G, respectively. A number of considerations might cause this interpretation to be open to question. These have been examined in several investigations (Nedoluha and Watson 1990; 1992; 1993). I describe below a likely process by which circular polarization can be created in masers that is quite different from the standard Zeeman effect.

When optical starlight passes through an interstellar medium in which the direction of alignment of the dust grains changes, the light becomes weakly circular polarized (Kemp and Wolstencroft 1972). It is an example of the creation of circular polarization in classical optics that occurs when linearly polarized radiation passes through an anisotropic medium (e.g., Rossi 1957) —the "theory of the quarter-wave plate". There are several related effects that might influence the interpretation of the circular polarization that is observed in the H_2O and SiO masers. One seems especially worthy of consideration because it is inherent to the transport of intense maser radiation in the presence of a magnetic field.

When the Zeeman frequency $g\Omega$ (i.e., the Zeeman energy shift divided by $\hbar$) is much greater than the rate R for stimulated emission due to the beam of maser radiation and the rate Γ for all other decay processes of the masing states, the direction of the magnetic field provides the axis of symmetry for the molecular quantum states. In the other extreme ($R >> g\Omega, \Gamma$), the direction of the beam of maser radiation provides an axis of symmetry. In either of these two extremes, the excitation of the gas and the resulting maser amplification can be calculated by considering only ordinary populations of the substates of the angular momentum ("magnetic substates") and rate equations. In the first case, the "z-axis" for the substates is parallel to the magnetic field and in the second, it is parallel to the direction of propagation. When the maser is at least partly saturated ($R \stackrel{\sim}{>} \Gamma$) and neither of these two extremes is appropriate (i.e., when $R \simeq g\Omega$), a convenient axis of symmetry no longer exists. Ordinary populations are no longer adequate for calculating the transfer of polarized radiation. The quantum mechanical density matrix (with "off-diagonal" matrix elements) commonly is used in this regime to describe the excitation. As a beam of maser radiation in a magnetic field propagates and is amplified so that R changes from $R << g\Omega$ to $R \simeq g\Omega$ along its path, the direction changes for the linear polarization of this radiation. By analogy with the example of starlight and the changing direction of alignment of the dust grains, circular polarization might be expected to be created.

Detailed calculations have been performed for this "intensity dependent circular polarization" described above for parameters appropriate for the 22 GHz water masers (Nedoluha and Watson 1990) and for the 43 GHz SiO masers (Nedoluha and Watson 1993). Significant circular polarization can be created. It has a spectral line profile for the Stokes V parameter that is antisymmetric about line center and thus resembles that produced by the ordinary Zeeman effect when there is no hyperfine structure. Such calculations are a challenge because the differential equations of radiative transfer must be integrated as a function of frequency. The solution requires the calculation of the full quantum mechanical density matrix (i.e., including off-diagonal elements) as a function of molecular velocity. Analytic estimates can be made that verify the numerical results (Nedoluha and Watson 1993). For both the SiO and H_2O masing transitions, fractional circular polarizations similar to what is observed can be calculated for magnetic fields that are much smaller than what is inferred based on the standard Zeeman interpretation. Only about 10 mG may be necessary to understand the SiO observations. Whether the observed circular polarizations are caused by this intensity dependent effect depends upon the magnitude of R in comparison with $g\Omega$ when the maser is at least partially saturated ($R > \Gamma$). Various evidence indicates that the 43 GHz SiO masers are at least partly saturated. The observed fractional polarization can then be created by magnetic fields that are weaker by a factor of about 10^3 than what is inferred with the standard Zeeman effect. For the 22 GHz water masers, the evidence for the intensity dependent effect is less compelling. After the original investigation (Nedoluha and Watson 1990), it was recognized—as a result of the analysis of linebreadths described in Section 3—that R for the 22 GHz masers is much smaller than the prevailing estimates so that typically $R < (\Gamma, \Gamma_v)_> \simeq 1s^{-1}$. The magnetic moment for the 22 GHz transition ($F = 7 - 6$) also is larger than that of SiO by a factor of nearly ten. It is thus more likely that $R \ll g\Omega$ for the 22 GHz water masers than for the 43 GHz SiO masers. In addition, the calculations that have been performed to represent the 22 GHz transition actually are performed for an angular momentum $J = 2 - 1$ transition. The difficulty of the calculation increases significantly with increasing angular momentum and with the presence of overlapping hyperfine components in the 22 GHz transition. The likelihood for deviations from the standard Zeeman circular polarization also tends to increase when the fractional linear polarization is large. No circular polarization was detected in the Orion flare even though it has unusually high linear polarization. High linear polarization is common for the SiO masers. In summary, the standard Zeeman interpretation seems to be valid for the 22 GHz observations. When modified slightly for the effect of overlapping hyperfine components, (Nedoluha and Watson 1992), magnetic fields are inferred that typically are a few tens of milligauss. The circular polarization of 43 GHz SiO masers probably is not due primarily to the standard Zeeman effect.

5. OPTIMISM FOR THE FUTURE

There is increasing emphasis on probing the small scale structure of astronomical phenomena as indicated by the current commitments to interferometry at higher frequencies and with long baselines, potentially extending into space. Because of their high surface brightnesses and small dimensions, masers will continue to provide ideal sources of radiation with which to probe astronomical phenomena utilizing these instruments. We can reasonably expect to understand better the mechanism by which mass is returned to the gas from late-type stars with more refined imaging of the circumstellar SiO, H_2O and OH masers. Spectral information and images of masers will better delineate the gas dynamics of star formation and, possibly, disk structures associated with stars and galactic nuclei. Space interferometry of extragalactic masers can provide directly distances to nearby galaxies that are free of the usual uncertainties. The role of the magnetic field in the gas dynamics of star formation and in other regions of activity in the molecular gas will be understood more clearly as a result of improved capabilities for the observation of polarized maser radiation.

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